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Effect of Elevated Air Temperature and Carbon Dioxide Levels on Dry Season Irrigated Rice Productivity in Bangladesh

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Abstract

Agricultural productivity is affected by air temperature and CO_2 concentration. The relationships among grain yields of dry season irrigated rice (*Boro*) varieties (BRRI dhan28, BRRI dhan29 and BRRI dhan58) with increased temperatures and CO_2 concentrations were investigated for futuristic crop management in six regions of Bangladesh using CERES-Rice model (DSSATv4.6). Maximum and minimum temperature increase rates considered were 0˚C, +1˚C, +2˚C, +3˚C and +4˚C and CO_2 concentrations were ambient (380), 421, 538, 670 and 936 ppm. At ambient temperature and CO_2 concentration, attainable grain yields varied from 6506 to 8076 kg·ha^{-1} depending on rice varieties. In general, grain yield reduction would be the highest (13% - 23%) if temperature rises by 4˚C and growth duration reduction would be 23 - 33 days. Grain yield reductions with 1˚C, 2˚C and 3˚C rise in temperature are likely to be compensated by increased CO_2 levels of 421, 538 and 670 ppm, respectively. In future, the highest reduction in grain yield and growth duration would be in cooler region and the least in warmer saline region of the country. Appropriate adaptive techniques like shifting in planting dates, water and nitrogen fertilizer management would be needed to overcome climate change impacts on rice production.

Keywords

Maximum Temperature, Minimum Temperature, CO_2 Levels, Regional Variability, Yield Compensation

1. Introduction

Bangladesh is a deltaic small country in South Asia with the 13th highest world population density and the population would be 202 million by 2050 [1]. All suitable lands are under cultivation, which is decreasing due to increasing demand for residential and industrial uses [2]. Besides, Bangladesh either enjoys food self-sufficiency or scarcity depending on natural calamities that are increasing in recent times [3] [4] [5]. Climate change associated sea level rise is expected to increase the risk for flooding and salinization of agricultural lands, especially near the southern coast [6] [7]. Increase of global mean surface temperatures for 2081-2100 relative to 1986-2005 is projected to be in the range of 0.3˚C to 4.8˚C depending on different Representative Concentrate Pathways [8]. Such changes will also be found in Bangladesh where average day temperature increase is likely to be 2.0˚C to 4.0˚C by 2100 [8].

Throughout the last 150 years, atmospheric CO_2 concentration has increased from 280 ppmv to 385 ppmv in 2008 (https://www.esrl.noaa.gov/gmd/ccgg/trends/) due to widespread human activities such as fossil fuel burning, cement production, and modified land-use patterns [9] [10]. At the current rate of atmospheric CO_2 increase it will be double before 2100 causing dramatic effects on global and regional-scale climate. Rainfall has become increasingly variable and has demonstrated an uneven distribution. This erratic pattern produces extreme events, such as floods and drought, which have shown noticeable adverse effects on rice yields [11] [12]. As a result, rice production is likely to decline by 8% - 17% by 2050 [13] [14].

Crop agriculture in Bangladesh is dominated by rice monoculture. Almost 80% of the total cropped area is planted with rice in different seasons, which accounts for more than 90% of total grain production [15] [16]. Among the rice growing seasons, dry season rice (*Boro*) contributed more than 53% of the total rice production in Bangladesh [15]. Food security is synonymous to rice security in Bangladesh. So, there is a crucial need to assess effects of climate change on rice productivity and economic growth of this country.

Some studies have recently investigated the economic effects of climate change on agricultural production in developing countries [17]-[23]. Although these studies showed susceptibility of crop agriculture to climate change, but the limited literatures on these are available for Bangladesh [24] [25] [26] [27] [28]. Ali [26] has discussed the influence of climate change by considering cyclones, storm surges, coastal erosion and backwater effects and reported large land losses in eastern part of Bangladesh because of beach erosion. Rashid & Islam [28] identified droughts, floods, soil salinity and cyclones as the major extreme climatic events that have affected agricultural production adversely. The CERES-Rice model and the DSSAT model was used to study the influence of higher air temperature and higher atmospheric CO_2 concentration on rice yield [29] [30] [31] with old varieties that are not found in the field now a day. Moreover, future climate change scenario delineation has been changed also. Therefore, the objective of this study was to assess the impact of climate change on dry season irrigated rice (*Boro*) production because of high temperatures and CO_2 concentrations in Bangladesh for futuristic adoption indication in agriculture.

2. Materials and Methods

2.1. Site Characterization

The study was conducted in six locations across the country of Bangladesh having diverse soil and weather conditions. The study locations were Gazipur (23˚45'N latitude, 90˚22'E longitude, 8.4 m above mean sea level [AMSL]), Rangpur (24˚41'N latitude, 89˚16'E longitude, 33.04 m AMSL), Rajshahi (24˚22'N latitude, 88˚22'E longitude, 17.24 m AMSL), Barisal (22˚41'N latitude, 90˚21'E longitude, 2.54 m AMSL), Comilla (23˚28'N latitude, 91˚09'E longitude, 6.54 m AMSL) and Habiganj (24˚25'N latitude, 91˚25'E longitude, 22.54 m AMSL) districts of Bangladesh.

2.2. Model Inputs Parameters

Selected input data used for CERES-Rice model are shown in Table 1.

2.2.1. Weather Data

Weather data for the study regions were collected from the Bangladesh Meteorological Department (BMD) for the period of 1981-2015. Base year daily average (to minimize unusual phenomenon) of maximum and minimum temperatures, rainfall and sunshine hours were calculated and created two successive

Table 1. Selected input data requirements for the CERES-Rice model (modified from [32] [33]).

Agronomic data	Pedological-hydrological data	Daily weather data
Sowing and transplanting date	Soil classification	Maximum and minimum air temperature
Row spacing: seeding depth	Texture	Precipitation
Number of plants hill^{-1}	Number of layers in soil profile	Solar radiation
Number of plants m^{-2}	Slope	
Age of seedling (day)	Permeability	
Base temperature to estimate phenological stages	Drainage	
Station information:	Soil layer depth	
Latitude	Soil horizon	
Longitude	Clay, silt, and sand content	
	Bulk density	
	Saturated hydraulic conductivity for each soil layer	
	Total nitrogen for each layer	
	Soil pH for each layer	
	Root quantity for each layer	

years' weather file for DSSAT format, because *Boro* rice grows from November in one year and ends at April or May in the next year. The seasonal model simulation was run in SIMMETEO mode for 30 years to capture temperature and CO_2 effects on yield and growth duration of selected varieties.

Extreme weather parameters like yearly number of cold spell duration indicator by taking annual count of days with at least 6 consecutive days when minimum temperature (<10th percentile) and number of warm spell indicator by taking annual count of days with at least 6 consecutive days when maximum temperature (>90th percentile) was estimated by using *RClimDex* v1.0 model software [34]. These indicators stated the cooler or warmer events of a particular area over the time spell.

2.2.2. Soil Parameters

Location-wise soil parameters used in DSSATv4.6 model is thickness of three layers, layer-wise sand, clay, bulk density, soil organic carbon and soil hydraulic characters. Soil pH, EC and slope also are required as inputs for different locations (Table 2). The terms "lower limit" and "drained upper limit" correspond to the permanent wilting point and field capacity, respectively [35].

2.2.3. Crop Parameters

BRRI dhan28, BRRI dhan29 and BRRI dhan58 were used for grain yield and growth duration under varying levels of increased temperatures and CO_2 concentrations. In all locations, selected varieties were tested against 15 November sowing, the optimum sowing date for *Boro* rice cultivation. In sowing date experiment, seeds were sown on 15 October to 30 December at 7 days interval to find out the optimum sowing date and to overcome the climatic effects for *Boro* rice growing.

Table 2. Physical and chemical properties of soils at the selected locations.

Attributes	Gazipur			Rangpur			Rajshahi			Barisal			Comilla			Habiganj		
Soil depth (cm)	20	40	60	20	40	60	20	40	60	20	40	60	20	40	60	20	40	60
WP (vol., frac.)	0.29	0.29	0.28	0.09	0.08	0.06	0.23	0.17	0.15	0.24	0.24	0.22	0.26	0.25	0.24	0.26	0.25	0.24
FC (vol., frac.)	0.45	0.43	0.40	0.28	0.22	0.26	0.41	0.35	0.35	0.44	0.44	0.44	0.41	0.39	0.38	0.41	0.39	0.39
Porosity (vol., frac.)	0.50	0.50	0.49	0.48	0.46	0.40	0.48	0.49	0.44	0.49	0.48	0.48	0.46	0.47	0.47	0.46	0.47	0.47
Ks (cm/hr)	0.32	0.35	0.32	1.10	0.89	0.81	0.15	0.48	0.48	0.15	0.14	0.14	0.17	0.19	0.19	0.29	0.21	0.19
BD (g/cc)	1.35	1.34	1.35	1.39	1.41	1.52	1.29	1.42	1.42	1.26	1.30	1.31	1.36	1.35	1.35	1.34	1.35	1.35
OC (%)	0.72	0.60	0.38	0.45	0.37	0.20	1.18	1.10	0.90	0.90	0.70	0.40	0.54	0.31	0.29	0.74	0.31	0.21
Clay (%)	48.0	48.0	47.0	17.0	8.0	5.0	60.0	35.0	37.0	34.0	36.0	34.0	46.0	44.0	42.0	45.0	44.0	42.0
Silt (%)	47.0	46.0	47.0	51.0	37.0	15.0	27.0	30.0	30.0	59.0	58.0	56.0	42.0	41.0	40.0	43.0	41.0	40.0
Total N (%)	0.07	0.06	0.04	0.04	0.03	0.02	0.15	0.12	0.10	0.09	0.07	0.04	0.05	0.03	0.03	0.07	0.03	0.02
pH	6.4	6.3	6.2	5.5	5.9	6.1	5.6	6.0	6.2	7.5	7.0	6.8	6.7	7.0	7.3	6.6	7.0	7.2

*WP-Wilting point, FC-field capacity, Ks-Saturated hydraulic conductivity, BD-Bulk density, OC-Organic carbon.

2.3. Yield Simulations

Potential yield is defined as the maximum yield of a variety restricted only by season-specific climatic conditions. This assumes that other inputs (nutrient, water, etc.) are non-limiting and cultural practices are optimal. Thus, the potential yield of a crop depends on the temporal variation in CO_2 level in the atmosphere, solar radiation, maximum and minimum temperatures during the crop growing season and physiological characteristics of the variety. Mechanistic crop growth models are routinely used to estimate potential yield and assess the effects of climate change [36] [37] [38] [39].

To simulate potential rice yield CERES-Rice v4.6 was used. This mechanistic model simulates crop growth and development processes, net photosynthesis based on radiation use efficiency, leaf area index, extinction coefficient and light absorption by the canopy [40]. The model can also simulate the effect of CO_2 on photosynthesis and water use based on stomatal conductivity [41].

Potential yields of BRRI dhan28, BRRI dhan29 and BRRI dhan58, the most popular varieties in dry season of Bangladesh, were simulated. Genetic coefficients used for those varieties are provided in **Table 3**. The coefficients were determined based on experiments by repeated iterations until a close match between simulated and observed phenology and yield was obtained. The data of field experiments were used for calibration and validation. There was a good agreement between simulated and observed phonological development and grain yield. The performance of the model has been well validated in Bangladesh [42].

2.4. Selection of Scenarios for Model Applications

In future, the rise in temperature is likely to be 2˚C to 4˚C by 2100 in South Asia including Bangladesh [8]. So, the CERES-Rice model was applied for normal (no temperature rise) and 1˚C, 2˚C, 3˚C and 4˚C rise over normal weather condition.

Table 3. Genetic coefficients of rice varieties used in DSSAT model.

Genetic coefficient parameters	Values		
	BRRI dhan28	BRRI dhan29	BRRI dhan58
Juvenile phase coefficient (P1), GDD[a]	825	950	850
Photoperiodism coefficient (P2R), GDD h^{-1}	150	150	150
Grain filling duration coefficient (P5), GDD	425	550	470
Critical photoperiod (P20), h	12.6	12.8	12.7
Spikelet number coefficient (G1)	50	60	55
Single grain weight (G2), g	0.022	0.021	0.021
Tillering coefficient (G3)	1.0	1.0	1.0
Temperature tolerance coefficient (G4)	1.0	1.0	1.0

[a]GDD, growing degree days (˚C).

During initial growth stage, *Boro* rice plants grow under cool and dry conditions but exposed to hot environment in flowering and harvesting stages. Although *Boro* rice growing season is generally uneventful, few localized thunder showers take place sometimes. It is found that temperature stress and resultant crop damage is a significant reason for reductions in *Boro* rice yield, especially with delayed established crop. According to CMIP5 and Earth System Model, predicted CO_2 concentrations will be reaching 421 ppm (RCP2.6), 538 ppm (RCP4.5), 670 ppm (RCP6.0), and 936 ppm (RCP 8.5) by the year 2100 [8]. So, we have selected those CO_2 levels and compared with ambient CO_2 concentration (380 ppm).

3. Results and Discussion

3.1. Grain Yields

Grain yields of selected rice varieties varied among regions mainly due to climatic variability and soil properties. In general, the highest potential grain yield was found in Rangpur and the lowest in Barisal region irrespective of varieties. Grain yield varied from 6.50 to 7.36, 7.29 to 8.08 and 6.84 to 7.80 $t \cdot ha^{-1}$ for BRRI dhan28, BRRI dhan29 and BRRI dhan58, respectively based on long-term (1981-2015) weather parameters (**Figure 1**). These variations are related with weather parameters and soil properties. Pathak [43] reported 7.7 to 10.7 $t \cdot ha^{-1}$ yield of wet season rice in Indo-Gangetic Plains (IGP). Aggarwal *et al.* [39] reported about 10 $t \cdot ha^{-1}$ rice yields in Punjub and Haryana. Mohandas *et al.* [44] also reported 10.5 $t \cdot ha^{-1}$ potential yield in Kapurthala district, Punjab but 7.1 $t \cdot ha^{-1}$ in Cuttack, Orissa. These clearly indicate that grain yield of rice varies across locations.

3.2. Weather Data and Its Extremes

Long-term (1981-2015) monthly mean weather data showed that mean maximum temperature varied from 23.0˚C to 36.1˚C for all the study regions. The

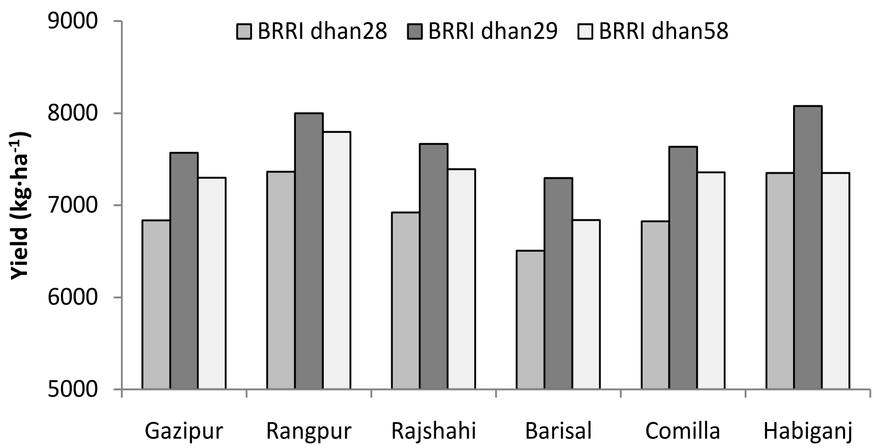

Figure 1. Grain yields of selected varieties under normalized weather conditions in different regions of Bangladesh.

lowest mean maximum temperature was found in January and the highest mean maximum temperature in April (Figure 2). The extreme high temperature (>35˚C) was recorded at Rajshahi location. Long-term mean minimum temperature varied from 10.4˚C to 25.0˚C. The lowest temperature was found at Rajshahi in January and the highest temperature at Barisal in May (Figure 2).

Climatic extreme events like five years' total number of cold spell duration were in decreasing trends in most of the regions, except a slight deviation in Rangpur and Rajshahi areas (Table 4), where cold spell was decreasing in 1996-2000 and then in increasing trend. Five years total number of warm spell duration was in increasing trends in most cases except in Rangpur region (Table 4). Since trend in warm spell is increasing, *Boro* rice crop might be exposed to unusual temperature in future and thus reduced production is most likely. *Boro* rice starts its journey in cooler and drier conditions and continue grow up to vegetative. Its flowering, ripening and harvesting stages are exposed to hot summer weather. So, *Boro* rice faces winter extreme cool and warm spells in its growing periods. Initially crop growth is hampered because of cold spell, but temperature is increasing in most regions and if temperature goes beyond 35˚C during heading and flowering stages, sterility increased resulting in reduced grain yield. Generally, any temperature below 20˚C and above 30˚C cause yield reduction in rice [45]. Horie *et al.* [46] also reported that as the average temperature increases above 22˚C - 23˚C, rice yield declined linearly up to 30˚C and decline sharply thereafter. The initial linear decrease was due to the shorter crop

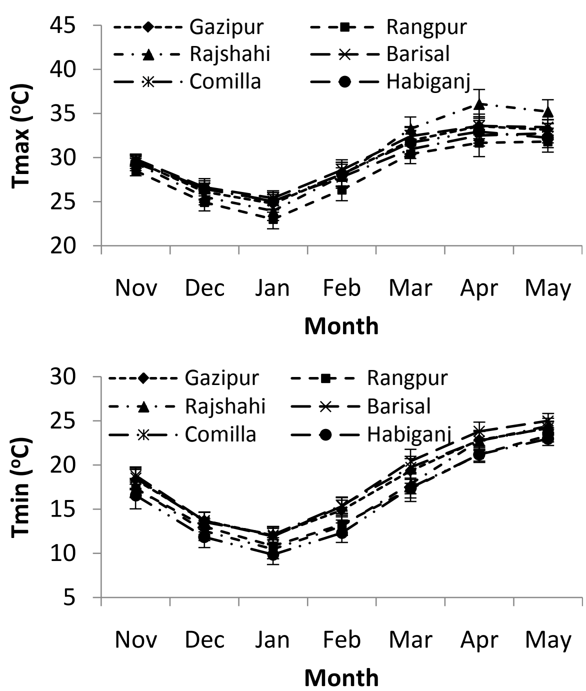

Figure 2. Long-term (1981-2015) monthly mean maximum and minimum temperature of the study regions during winter season. Error bar indicate the standard deviation.

Table 4. Number of cold and warm spells duration during 1981 to 2015 in the study regions of Bangladesh.

Year	Gazipur		Rangpur		Rajshahi		Barisal		Comilla		Habiganj	
	Cold spell (d)	Warm spell (d)	Cold spell (d)	Warm spell (d)	Cold spell (d)	Warm spell (d)	Cold spell (d)	Warm spell (d)	Cold spell (d)	Warm spell (d)	Cold spell (d)	Warm spell (d)
1981-85	0	19	0	6	17	21	27	27	23	13	21	0
1986-90	7	60	19	18	31	60	8	14	12	13	40	12
1991-95	7	31	43	8	23	40	25	7	58	7	41	13
1996-00	7	44	8	32	6	38	32	29	26	27	7	75
2001-05	0	20	12	7	12	42	0	6	0	28	0	51
2006-10	6	32	15	0	30	50	20	27	6	26	12	96
2011-15	0	44	40	7	22	71	7	38	0	18	0	79

duration caused by increased temperature and the sharp decline after 30˚C was because of spikelet sterility from high temperature damage.

3.3. Effect of CO_2 and Temperature on Yield

Grain yields decreased with increase in temperatures at 380, 421, 538, 670 and 936 ppm CO_2 levels; although it improved with increasing CO_2 levels for a specific temperature rise (**Figures 3-5**). Increase in grain yields were 2.6% - 2.8% for RCPs 2.6, 10.8% - 11.8% for RCPs 4.5 and 19.4% - 21.2% for RCPs 6.0 and 32.7% - 37.1% for RCPs 8.5 with varied CO_2 levels. The highest yield increase was 40.3% with BRRI dhan28, 33.6% with BRRI dhan29 and 40.3% with BRRI dhan58 rice varieties at 936 ppm CO_2. In all regions of Bangladesh, predicted mean yield reduction was 4.77%, 3.44% and 5.03% per degree rise in temperature for BRRI dhan28, BRRI dhan29 and BRRI dhan58, respectively at 380 ppm CO_2 level. Mahmood [24] reported 9.7% - 22.7% yield reduction at Mymensingh and 7.3% - 17.0% at Barisal with BR3 depending on temperature rise. This indicates that rice production will be in decreasing trends in future if climate smart practices are not adopted. Grain yield reduction rates were higher with short and medium growth duration rice varieties compared to long duration BRRI dhan29. Among the study studied regions, grain yield reductions were the lowest (0.7% - 16.4%) in Barisal irrespective of temperature rise with all the tested varieties and CO_2 levels (**Tables 6-8**). Since minimum temperature range is generally higher in Barisal regions during *Boro* season (**Figure 2**), attainable yield is low (**Figure 1**) compare to other tested regions and thus less grain yield reduction is likely because of temperature rise in future. Long duration variety (BRRI dhan29) had the lowest grain reduction (12.2% - 15.4%) compared to other tested varieties irrespective of regions and CO_2 levels (**Tables 6-8**). Crop duration reduces with increased temperature, but its influence is more prominent with short duration variety. So, higher grain yield is expected in future with existing long duration varieties than others. The scenario could be changed in future with the development of cool variety. In Rangpur region, grain yield reduction with BRRI dhan29

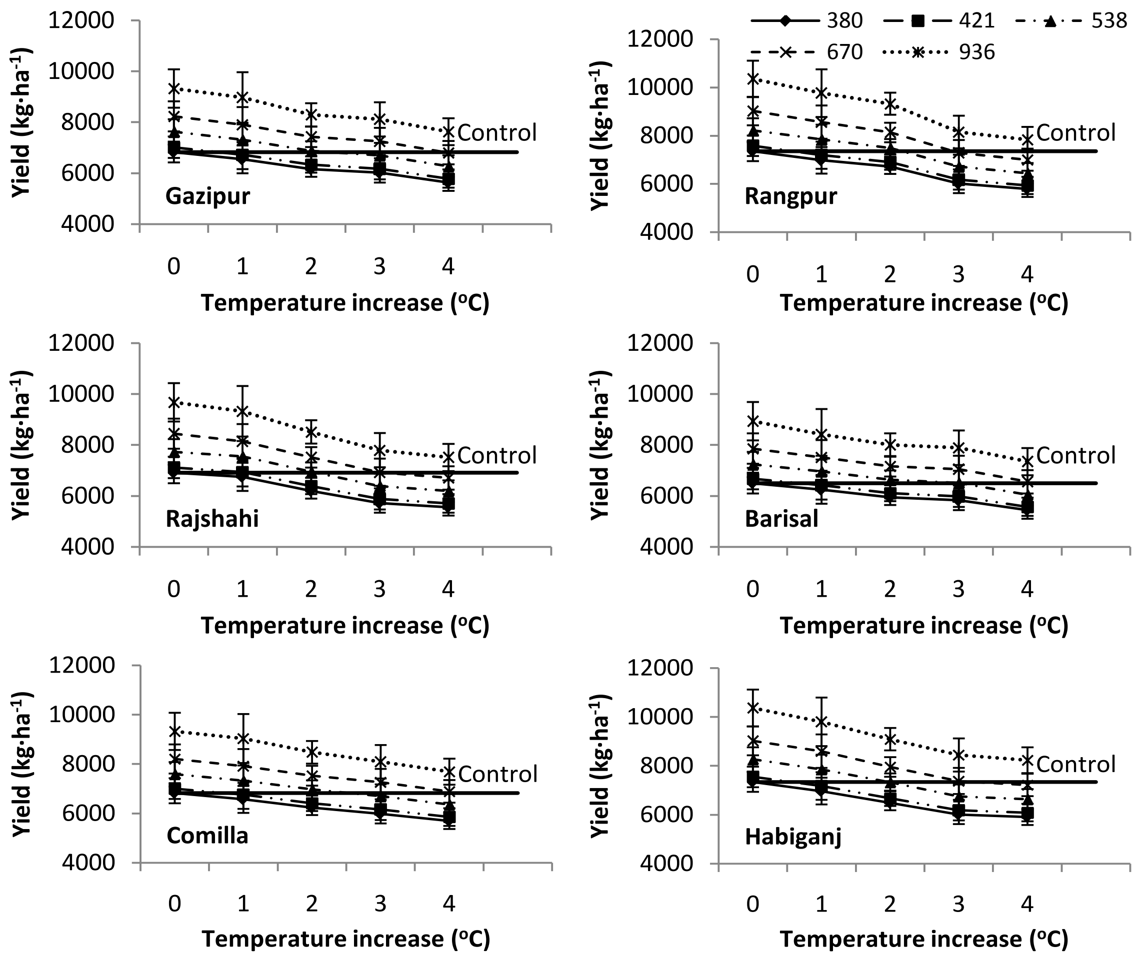

Figure 3. Estimated rice yield of BRRI dhan28 under varied temperature and CO_2 levels in different regions of Bangladesh; Error bars indicate the standard deviation.

was minimum (0.4% - 3%) because of temperature rise up to 2˚C. This part of the country generally enjoys cooler environment for a longer period in winter season and thus predicted temperature increase by 2˚C might not be hazardous for *Boro* rice production in future.

Grain yield reduction as predicted through the use of ORYZA1 and INFOCROP rice models with 1˚C increase in temperature was 7.20% and 6.66%, respectively at 380 ppm CO_2 level [47]. Increased CO_2 concentration up to 700 ppm, however, showed 30.73% and 56.37% higher yield by ORYZA1 and INFOCROP crop model, respectively. When temperature was increased by about 4˚C above the ambient level, ORYZA1 predicted yield reductions of 7.63%, 9.38% and 15.86%, respectively based on General Fluid Dynamics Laboratory (GFDL) Model, Goddard Institute of Space Studies (GISS) model and the United Kingdom Meteorological Office (UKMO) model; while INFOCROP predicted reductions of 9.02%, 11.30% and 21.35%. We have found less yield reduction than their findings. Moreover, IPCC [14] and BBS [48] estimated 8% - 17% decline in rice production by 2050 in South Asian region which is similar to our findings.

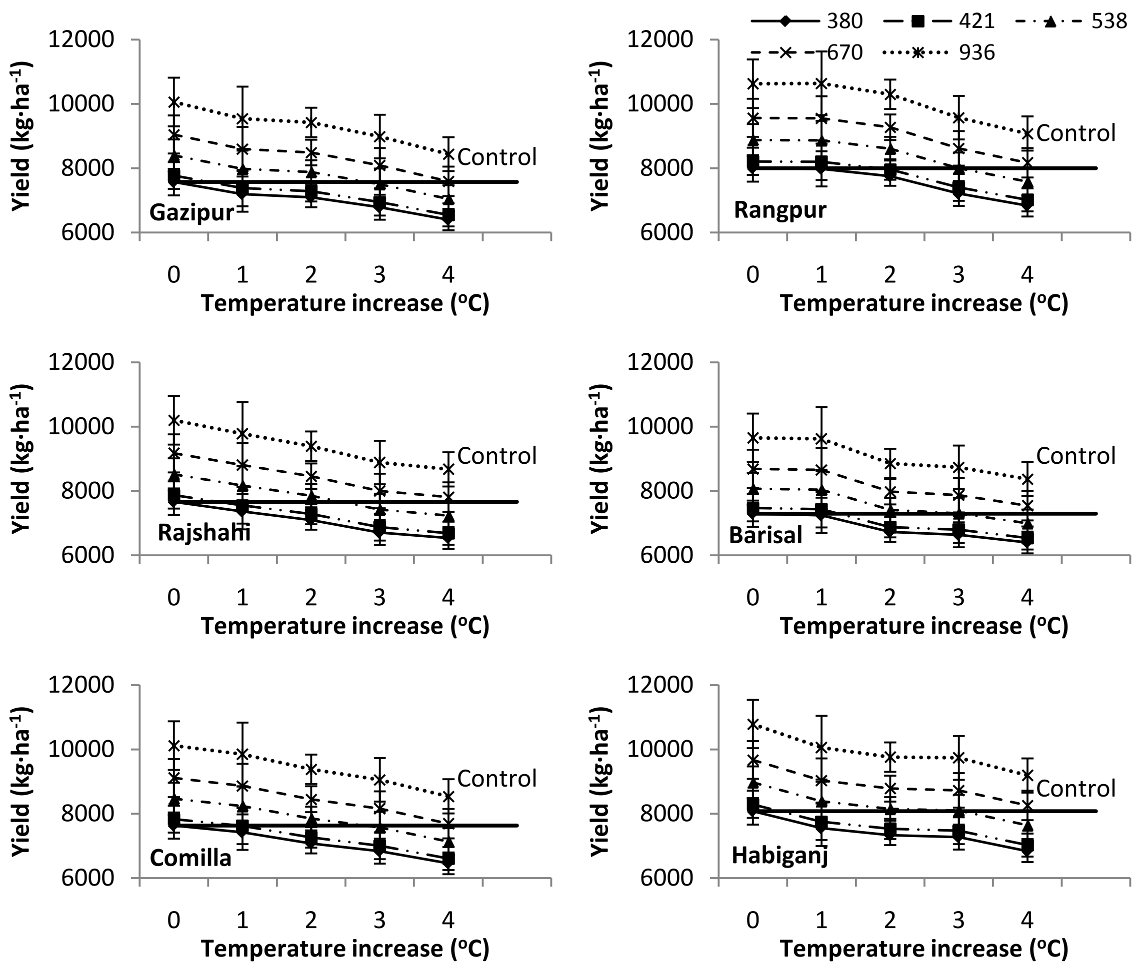

Figure 4. Estimated rice yield of BRRI dhan29 under varied temperature and CO_2 levels in different regions of Bangladesh; Error bars indicate the standard deviation.

An increase in air CO_2 level generally increased crop yield because of stimulated photosynthetic processes and improved water use efficiency [49]. In general, the effect of increased temperature would be negative because of increasing respiration [50] and a shortened vegetative and grain filling period [46]. Although major rice models indicate about 5% yield reduction for every degree rise in mean temperature [51] and Dias *et al.* [52] estimated 25% - 35% yield reduction in Sri Lanka using DSSAT. Basak *et al.* [31] reported 20% and 50% yield reduction by 2050 and 2070, respectively in *Boro* season with BR3 and BR14 rice varieties. These greater predicted yield reductions could be because of response behavior of studied varieties or use of inappropriate genetic coefficients in the model.

All the study regions had lower minimum average temperature at sowing (middle of November) and transplanting (January) time and it increased during tillering, panicle initiation and flowering stages. After nineties, cold spell at Rangpur and Rajshahi areas was is increasing trend that might have inflicted cold injury of *Boro* rice seedlings (**Table 4**). In Gazipur, Rajshahi and Habiganj

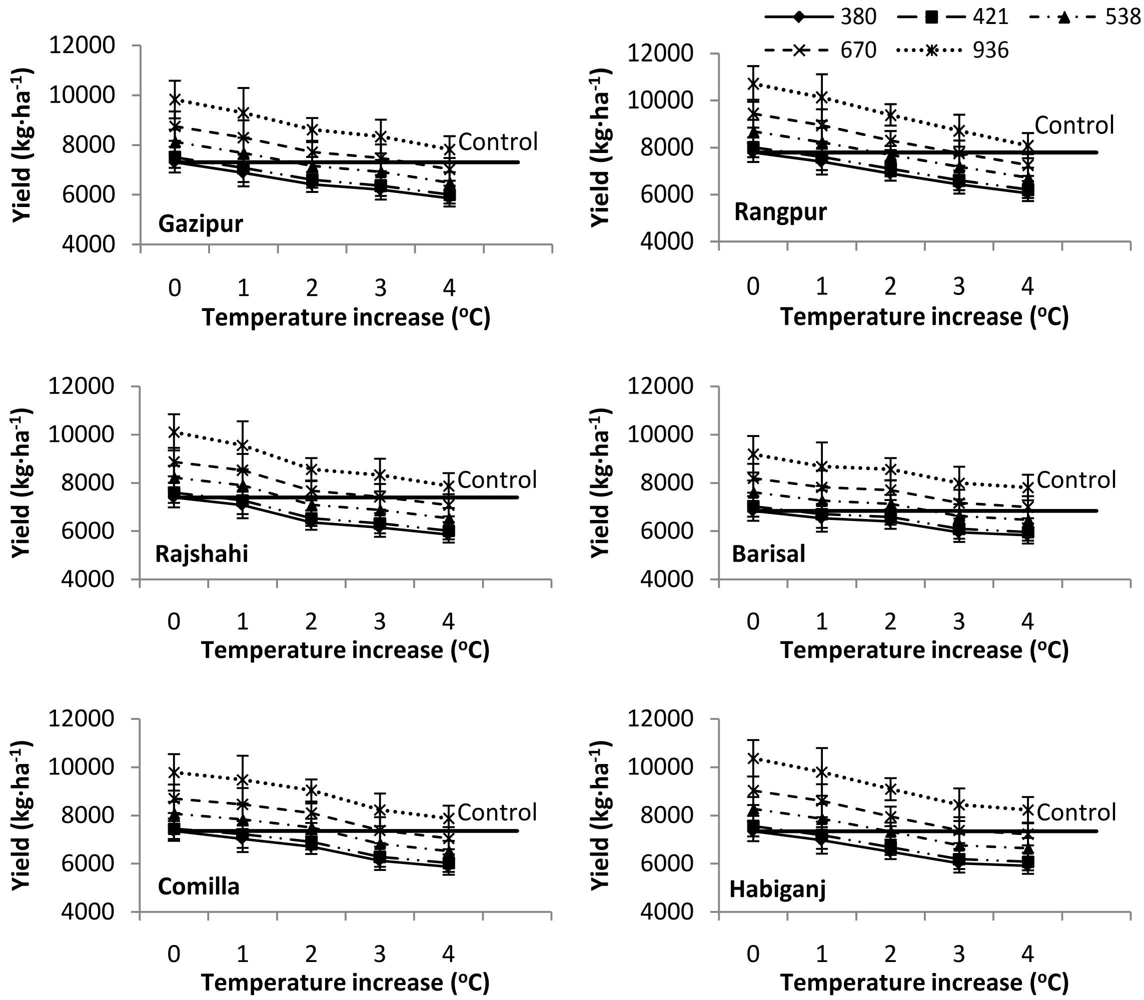

Figure 5. Estimated rice yield of BRRI dhan58 under varied temperature and CO_2 levels in different regions of Bangladesh; Error bars indicate the standard deviation.

regions, warm spells were in increasing trend resulting in reduced rice production in those areas (**Table 4**). At flowering stage, maximum temperature was about 33.3˚C - 36.1˚C in Rajshahi, 31.9˚C - 33.6˚C in Gazipur, 30.4˚C - 31.7˚C in Rangpur, 32.4˚C - 33.6˚C in Barisal, 30.9˚C - 32.5˚C in Comilla and 31.7˚C - 32.9˚C in Habiganj regions and sometimes it goes beyond the critical level (>35˚C). High temperature generally prevails in March through May (**Figure 2**) and thus spikelet sterility and increased respiratory loss are most likely depending on growth stages of rice crops. Rice pollen viability and its production decline as daytime maximum temperature exceeds 33˚C and ceases beyond 40˚C [53]. In grain filling stage, kernel weight of rice decreases greatly below and above 24˚C temperature [54]. In the projected climate change scenarios, the maximum temperature at flowering stage of rice will be beyond the critical limit and thus reduction of rice yield is a must. To avoid this situation, shifting the sowing window of *Boro* rice and to develop cold and heat tolerant rice varieties may be the option for sustaining food security in Bangladesh.

3.4. Effects of CO_2 and Temperature on Growth Duration

In all studied regions, growth duration of rice varieties was not significantly influenced by CO_2 levels but it was reduced by 7.45, 7.49 and 7.88 days for BRRI dhan28, BRRI dhan29 and BRRI dhan58, respectively with every degree increase in temperature compared to ambient temperature (**Figure 6** and **Table 5**). Mahmood [24] also reported 7 - 8 days reduced growth duration of BR3 per 1˚C rise in temperature. Biswas *et al.* [55] reported that both growth duration and grain yield of rice reduces depending on planting time. The lowest growth duration reduction was predicted for Barisal and Rajshahi regions for all temperature levels (**Table 5**). Since growth duration influences grain yield in most cases, reduced life span might be the cause of reduced yield in future.

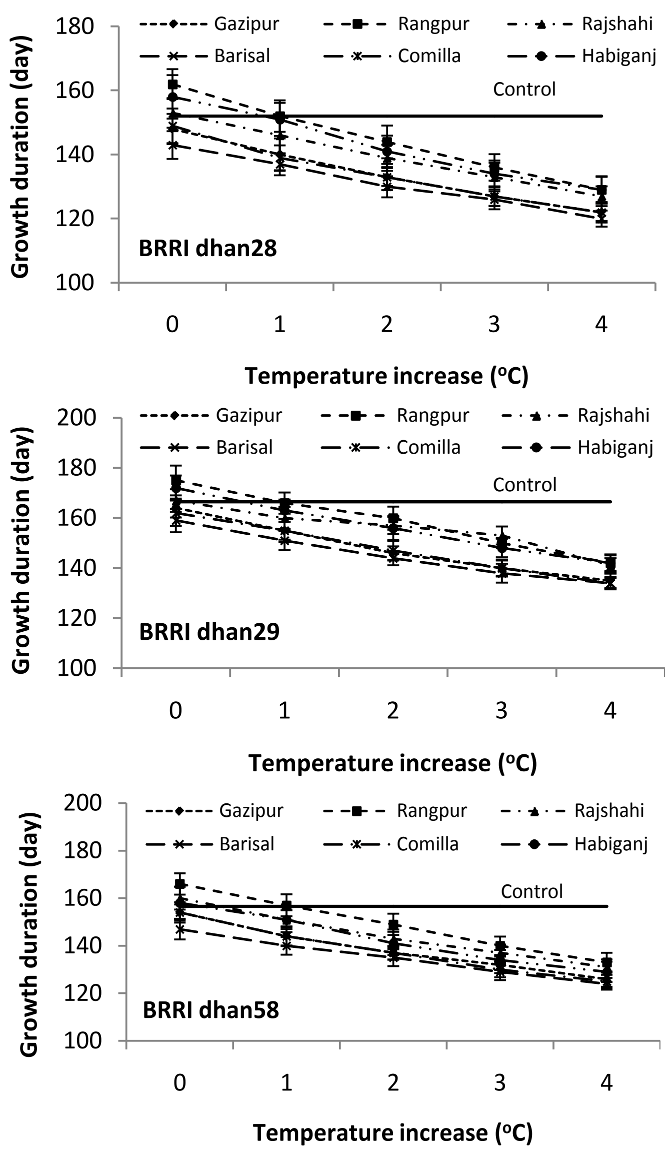

Figure 6. Growth durations of BRRI dhan28, BRRI dhan29 and BRRI dhan58 as affected by temperature under different regions of Bangladesh; Error bars indicate the standard deviation.

Table 5. Growth duration reductions (days) with different varieties at varied regions of Bangladesh.

Locations	BRRI dhan28				BRRI dhan29				BRRI dhan58			
	Increase in temperature											
	+1	+2	+3	+4	+1	+2	+3	+4	+1	+2	+3	+4
Gazipur	8	15	21	26	9	18	24	29	10	17	22	28
Rangpur	10	18	26	33	9	15	25	33	9	17	26	33
Rajshahi	7	14	20	26	7	10	14	26	9	17	23	29
Barisal	6	13	17	23	8	15	21	25	7	12	18	23
Comilla	10	16	22	27	7	15	22	28	10	17	24	29
Habiganj	7	17	24	29	9	16	24	30	7	17	24	29

3.5. Combined Effects of Temperature and CO_2 on Yield

At the ambient CO_2 concentration, grain yield of rice is likely to be reduced by 16.4% - 21.3% for BRRI dhan28 (Table 6), 12.2% - 15.4% for BRRI dhan29 (Table 7) and 14.8% - 22.3% for BRRI dhan58 (Table 8) if temperature increases by 4˚C. But 936 ppm CO_2 concentration (RCPs 8.5) might increase yield by 36.6% - 41.1% for BRRI dhan28 (Table 6), 32.3% - 33.6% for BRRI dhan29 (Table 7) and 33.1% - 41.1% for BRRI dhan58 (Table 8) in different regions of Bangladesh with existing temperature pattern. In most areas, BRRI dhan28 showed a competitive yield advantage under ambient conditions (no temperature rise and 380 ppm CO_2) that extended up to 2˚C temperature rise with 538 ppm CO_2 level except in southern Bangladesh. Grain yield reduction due to 3˚C temperature rise could be compensated up to 670 ppm CO_2 level in all studied regions except in Rangpur areas. Similarly, if CO_2 936 ppm level might be able to compensate grain yield reduction due to 4˚C rise in all test regions of Bangladesh (Table 6). BRRI dhan29 showed similar trends and are more tolerant to adverse conditions than BRRI dhan28. In Rangpur and Habiganj regions, grain yield reductions due to 3˚C rise were compensated with 538 ppm CO_2 level; but in Gazipur, Rajshahi and Comilla regions, yield compensation is likely for 2˚C under same CO_2 level. Grain yield reductions because of temperature rise up to 4˚C are likely to be compensated by the presence of 670 ppm CO_2 for all the studied regions for BRRI dhan29 (Table 7). BRRI dhan58 showed more vulnerable in response to elevated temperature. In most of the regions, yield compensation is likely for 1˚C temperature rise with 538 ppm CO_2 except Barisal and Comilla regions. Yield compensation could be extended for 3˚C temperature rise by 670 ppm CO_2 level except in Rangpur areas and 936 ppm CO_2 for 4˚C temperature rise in all test regions (Table 8). Baker *et al.* [49] and Figueiredo *et al.* [56] also reported that yield reduction due to higher temperature can be compensated with increased CO_2 level. Horie *et al.* [57] reported that 100 μmol·mol^{-1} increased in CO_2 concentration gave 7% - 8% greater rice yield in Japan, but 2˚C rise in temperature significantly reduced such beneficial effect.

Table 6. Percent changes in grain yield as affected by increased temperature and elevated CO_2 concentration over control (no temperature rise, 380 ppm CO_2) for BRRI dhan28 at various test regions of Bangladesh.

CO_2 level (ppm)	Temperature rise (˚C)									
	Gazipur					Rangpur				
	0	+1	+2	+3	+4	0	+1	+2	+3	+4
380	0.0	−4.2	−9.7	−11.9	−17.5	0.0	−5.1	−8.7	−18.3	−21.3
421	2.8	−1.5	−7.2	−9.6	−15.2	2.9	−2.3	−6.1	−16.0	−19.3
538	11.7	7.1	0.8	−1.8	−8.1	11.7	6.6	1.8	−8.7	−12.5
670	20.6	15.7	8.7	6.1	−0.4	22.6	16.3	10.5	−1.0	−4.9
936	36.6	31.3	21.4	18.8	11.7	40.6	32.6	26.6	10.8	6.5
	Rajshahi					Barisal				
380	0.0	−2.4	−10.3	−17.2	−19.6	0.0	−4.0	−8.5	−10.3	−16.4
421	2.9	0.3	−7.6	−14.9	−17.4	2.7	−1.3	−6.0	−7.9	−14.3
538	11.8	9.2	0.5	−7.6	−10.4	11.3	7.2	2.1	0.1	−7.0
670	22.0	17.7	8.6	0.2	−2.9	20.9	15.6	10.2	8.4	0.9
936	40.0	34.8	23.1	12.8	8.6	37.3	29.5	23.0	21.4	13.0
	Comilla					Habiganj				
380	0.0	−3.6	−8.5	−12.3	−16.4	0.0	−5.2	−11.7	−18.1	−19.5
421	2.8	−0.9	−6.0	−9.8	−14.2	2.8	−2.3	−9.1	−15.7	−17.1
538	11.3	7.5	2.3	−1.8	−6.7	12.5	6.9	−0.2	−8.0	−9.7
670	20.4	16.2	10.4	6.5	1.1	22.8	17.1	8.3	0.5	−1.7
936	36.7	32.5	24.3	18.6	12.8	41.1	33.4	23.7	15.0	12.1

Table 7. Percent changes in grain yield as affected by increased temperature and elevated CO_2 concentration over control (no temperature rise, 380 ppm CO_2) for BRRI dhan29 at various test regions of Bangladesh.

CO_2 level (ppm)	Temperature increase level									
	Gazipur					Rangpur				
	0	+1	+2	+3	+4	0	+1	+2	+3	+4
380	0.0	−5.0	−6.3	−10.3	−15.4	0.0	−0.2	−3.0	−9.8	−14.6
421	2.7	−2.4	−3.8	−8.2	−13.5	2.7	2.5	−0.4	−7.4	−12.3
538	11.0	5.5	4.1	−0.8	−6.9	11.0	10.9	7.7	0.1	−5.2
670	19.5	13.6	12.1	6.9	0.3	19.6	19.5	16.0	7.8	2.1
936	32.9	26.1	24.5	18.7	11.5	32.9	33.0	28.8	19.7	13.5
	Rajshahi					Barisal				
380	0.0	−4.0	−7.4	−12.5	−14.7	0.0	−0.7	−7.8	−9.0	−12.2
421	2.7	−1.4	−5.0	−10.3	−12.8	2.5	1.9	−5.7	−6.9	−10.4
538	11.1	6.6	2.5	−3.2	−5.6	10.7	10.2	1.6	0.1	−4.0
670	19.6	14.8	10.3	4.3	1.9	19.1	18.7	9.4	7.9	3.4
936	33.0	27.5	22.6	15.9	13.1	32.3	31.8	21.4	19.8	14.8
	Comilla					Habiganj				
380	0.0	−2.7	−7.3	−10.4	−15.4	0.0	−6.5	−9.2	−9.9	−15.4
421	2.6	−0.2	−4.9	−8.2	−13.4	2.7	−4.0	−6.8	−7.5	−13.0
538	10.9	7.9	2.8	−0.8	−6.6	11.1	3.9	0.9	0.3	−5.4
670	19.4	16.2	10.7	6.9	0.7	19.7	11.9	8.7	8.1	2.3
936	32.5	29.0	22.9	18.6	11.9	33.6	24.5	20.8	20.6	13.8

Table 8. Percent changes in grain yield as affected by increased temperature and elevated CO_2 concentrations over control (no temperature rise, 380 ppm CO_2) for BRRI dhan58 at various test regions of Bangladesh.

CO_2 level (ppm)	Temperature increase level									
	Gazipur					Rangpur				
	0	+1	+2	+3	+4	0	+1	+2	+3	+4
380	0.0	−5.7	−12.0	−15.1	−19.7	0.0	−5.0	−11.5	−17.5	−22.3
421	2.7	−3.0	−9.7	−12.8	−17.7	2.7	−2.5	−9.0	−15.2	−20.2
538	11.2	5.1	−2.0	−5.2	−11.1	11.3	5.6	−1.3	−7.9	−13.8
670	19.9	13.7	5.7	2.5	−3.8	21.0	14.7	6.5	−0.4	−6.9
936	34.5	27.3	18.1	14.2	7.2	37.3	29.9	20.4	11.8	3.7
	Rajshahi					Barisal				
380	0.0	−4.2	−14.0	−16.8	−20.7	0.0	−4.5	−6.3	−13.1	−14.8
421	2.7	−1.6	−11.6	−14.4	−18.6	2.7	−1.9	−3.7	−10.8	−12.8
538	11.1	6.8	−4.1	−7.0	−11.6	11.2	6.2	4.3	−3.0	−5.5
670	19.9	15.3	3.8	0.4	−4.3	19.8	14.4	12.5	4.9	2.3
936	36.6	29.3	15.9	12.6	6.5	34.3	27.0	25.3	16.9	14.1
	Comilla					Habiganj				
380	0.0	−4.4	−8.8	−16.8	−20.1	0.0	−5.2	−11.7	−18.1	−19.5
421	1.3	−1.7	−6.2	−14.5	−18.1	2.8	−2.3	−9.1	−15.7	−17.1
538	9.7	6.6	1.9	−7.1	−11.3	12.5	6.9	−0.2	−8.0	−9.7
670	18.2	14.9	10.0	0.4	−4.1	22.8	17.1	8.3	0.5	−1.7
936	33.1	28.9	22.9	12.0	7.0	41.1	33.4	23.7	15.0	12.1

4. Conclusion

This study was conducted to determine the effect of increased daily maximum and minimum temperatures and elevated CO_2 levels using CERES-Rice model on grain yield and growth duration of dry season rice (*Boro*) at six representative locations across Bangladesh. Long-term normalized weather data were used to predict grain yields of those varieties under variable increased temperature and CO_2 levels. Temperature increase rate considered was 0, +1˚C, +2˚C, +3˚C and +4˚C with the elevated CO_2 concentrations of 380, 421, 538, 670 and 936 ppm based on different RCPs. Rice grain yield was reduced by 256 - 403 kg·ha^{-1} for BRRI dhan28, 172 - 370 kg·ha^{-1} for BRRI dhan29 and 268 - 432 kg·ha^{-1} for BRRI dhan58 per 1˚C temperature rise. On the contrary, CO_2 concentration compensated yield by 225 - 275 kg·ha^{-1} for BRRI dhan28, 230 - 267 kg·ha^{-1} for BRRI dhan29 and 198 - 275 kg·ha^{-1} for BRRI dhan58 per 50 ppm CO_2 rise. In general, grain yield reduction and compensation rate were lower in warmer region and higher in cooler region. Growth duration was reduced by about 9 days irrespective of locations and varieties with an exception for BRRI dhan58, which has comparatively less growth duration reduction per degree temperature rise. In the projected climate change scenarios, maximum temperature at flowering stage of rice might cross the critical limit and thus reduction in rice yield is expected. To avoid this situation, shifting of sowing window for *Boro* rice and to develop cold and heat tolerant rice varieties would be the options for sustaining food security in Bangladesh and similar environments in other parts of the world.

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References

[1] UN (United Nations) (2015) United Nations Department of Economic and Social Affairs. World Population Prospects, the 2015 Revision. http://esa.un.org/wpp/unpp/ panel_population.htm

[2] Hasan, M.N., Hossain, M.S., Bari, M.A. and Islam, M.R. (2013) Agricultural Land Availability in Bangladesh. SRDI, Dhaka, 42.

[3] MoEF (Ministry of Environment and Forest) (2005) National Adaptation Program of Action (NAPA). Government of Bangladesh, Dhaka.

[4] DoE (Department of Environment) (2007) Climate Change and Bangladesh. Ministry of Environment and Forest, Government of Bangladesh, Dhaka.

[5] Huq, S. and Rabbani, G. (2011) Climate Change and Bangladesh: Policy and Institutional Development to Reduce Vulnerability. *Journal of Bangladesh Studies*, **13**, 1-10.

[6] Hossain, A. and Silva, J.A.T. (2013) Wheat Production in Bangladesh: Its Future in the Light of Global Warming. *AoB Plants*, 5, pls042. https://doi.org/10.1093/aobpla/pls042

[7] MoA-FAO (2012) Master Plan for Agricultural Development in the Southern Region of Bangladesh. Ministry of Agriculture (MoA, Government of Bangladesh) and United Nations Food and Agriculture Organization, Dhaka, 122.

[8] IPCC (2013) Summary for Policymakers. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M., Eds., *Climate Change* 2013: *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York.

[9] IPCC (1996) Climate Change 1995: The Science of Climate Change. In: Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A. and Maskell, K., Eds., *Climate Change* 1995: *The Science of Climate Change*, Cambridge University Press, Cambridge, 572.

[10] Fan, Y., Liang, Q.M., Wei, Y.M. and Okada, N. (2007) A Model for China's Energy Requirements and CO_2 Emissions Analysis. *Environmental Modelling & Software*, **22**, 378-393. https://doi.org/10.1016/j.envsoft.2005.12.007

[11] UNDP (United Nations Development Program) (2008) Fighting Climate Change: Human Solidarity in a Divided World. Human Development Report. Oxford University Press, Oxford.

[12] GOB (Government of Bangladesh) & UNDP (United Nations Development Program) (2009) The Probable Impacts of Climate Change on Poverty and Economic Growth and Options of Coping with Adverse Effects of Climate Change in Bangla-

desh. Policy Study, Dhaka.

[13] BBS (Bangladesh Bureau of Statistics) (2015) Yearbook of Agricultural Statistics of Bangladesh. Government of Bangladesh, Dhaka.

[14] IPCC (Intergovernmental Panel on Climate Change) (2007) Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

[15] BBS (Bangladesh Bureau of Statistics) (2016) Yearbook of Agricultural Statistics of Bangladesh. Government of Bangladesh, Dhaka.

[16] Asaduzzaman, M., Ringler, C., Thurlow, J. and Alam, S. (2010) Investing in Crop Agriculture in Bangladesh for Higher Growth and Productivity, and Adaptation to Climate Change. Bangladesh Food Security Investment Forum, Dhaka.

[17] Gbetibouo, G.A. and Hassan, R.M. (2005) Measuring the Economic Impact of Climate Change on Major South African Crops: A Ricardian Approach. *Global and Planetary Change*, **47**, 143-152. https://doi.org/10.1016/j.gloplacha.2004.10.009

[18] Kurukulasuriya, P. and Ajwad, M.I. (2007) Application of the Ricardian Technique to Estimate the Impact of Climate Change on Smallholder Farming in Sri Lanka. *Climatic Change*, **81**, 39-59. https://doi.org/10.1007/s10584-005-9021-2

[19] Haim, D., Shechter, M. and Berliner, P. (2008) Assessing the Impact of Climate Change on Representative Field Crops in Israel Agriculture: A Case Study of Wheat and Cotton. *Climatic Change*, **86**, 425-440. https://doi.org/10.1007/s10584-007-9304-x

[20] Sanghi, A. and Mendelsohn, R. (2008) The Impact of Global Warming on Farmers in Brazil and India. *Global Environmental Change*, **18**, 655-665. https://doi.org/10.1016/j.gloenvcha.2008.06.008

[21] Deressa, T.T. and Hassan, R.M. (2009) Economic Impact of Climate Change on Crop Production in Ethiopia: Evidence from Cross-Section Measures. *Journal of African Economies*, **18**, 529-554. https://doi.org/10.1093/jae/ejp002

[22] Moula, E.L. (2009) An Empirical Assessment of the Impact of Climate Change on Smallholder Agriculture in Cameroon. *Global and Planetary Change*, **67**, 205-208. https://doi.org/10.1016/j.gloplacha.2009.02.006

[23] Wang, J., Mendelsohn, R., Dinar, A., Huang, J., Rozelle, S. and Zhang, L. (2009) The Impact of Climate Change on China's Agriculture. *Agricultural Economics*, **40**, 323-337. https://doi.org/10.1111/j.1574-0862.2009.00379.x

[24] Mahmood, R. (1998) Air Temperature Variations and Rice Productivity in Bangladesh: A Comparative Study of the Performance of the YIELD and CERES-Rice Models. *Ecological Modelling*, **106**, 201-212. https://doi.org/10.1016/S0304-3800(97)00192-0

[25] Paul, B.K. (1998) Coping Mechanism Practiced by Drought Victims (1994/5) in North Bengal, Bangladesh. *Applied Geography*, **18**, 355-373. https://doi.org/10.1016/S0143-6228(98)00026-5

[26] Ali, A. (1999) Climate Change Impacts and Adaptation Assessment in Bangladesh. *Climate Research*, **12**, 109-116. https://doi.org/10.3354/cr012109

[27] Rahman, M.S. (2000) A Rainfall Simulation Model for Agricultural Development in Bangladesh. *Discrete Dynamics in Nature and Society*, **5**, 1-7. https://doi.org/10.1155/S1026022600000339

[28] Rashid, M.H. and Islam, M.S. (2007) Adaptation to Climate Change for Sustainable Development of Bangladesh Agriculture. Bangladesh Country Paper.

[29] Karim, Z., Hussain, S. and Ahmed, M. (1996) Assessing Impacts of Climate Variations on Food Grain Production in Bangladesh. *Water, Air, & Soil Pollution*, **92**, 53-62.

[30] Mahmood, R., Legates, D.R. and Meo, M. (2004) The Role of Soil Water Availability in Potential Rainfed Rice Productivity in Bangladesh: Applications of the CERES-Rice Model. *Applied Geography*, **24**, 139-159. https://doi.org/10.1016/j.apgeog.2004.03.001

[31] Basak, J.K., Ali, M.A., Islam, M.N. and Rashid, M.A. (2010) Assessment of the Effect of Climate Change on *Boro* Rice Production in Bangladesh Using DSSAT Model. *Civil Engineering Journal*, **38**, 95-108.

[32] Ritchie, J.T., Alocilja, E.C., Singh, U. and Uehara, G. (1987) IBSNAT and the CERES-Rice Model. *Proceedings of the International Workshop on the Impact of Weather Parameters on Growth and Yield of Rice*, Manilla, 7-10 April 1986, 271-281.

[33] Tsuji, G.Y., Uehara, G and Balas, G. (1994) DSSAT Version 3, Vols. 1-3. University of Hawaii, Hawaii.

[34] Zhang, X. and Yang, F. (2004) RClimDex 1.0 User Manual. Climate Research Branch, Environment Canada, Downsview.

[35] Ritchie, J.T. (1991) Wheat Phasic Development. In: Hanks, J. and Ritchie, J.T., Eds., *Modelling Plant and Soil System*, Agron. Mongr., ASA, CSSA, Medison, 31.

[36] Kropff, M.J., van Laar, H.H. and Matthews, R.B. (1994) ORYZA1: An Eco-Physical Model for Irrigated Rice Production. In: *SARP Research Proceedings*, IRRI, Los Banos, Philippines, and AB-DLO, Wageningen, 110 p.

[37] Kropff, M.J., Teng, P.S., Aggarwal, P.K., Bouman, B.A.M. and van Laar, H.H. (1997) Application of Systems Approaches at the Field Level. Vol. 2, Kluwer Academic Publishers, Dordrecht, 465 p. https://doi.org/10.1007/978-94-017-0754-1

[38] Aggarwal, P.K., Kropff, M.J., Cassman, K.G. and ten Berge, H.F.M. (1997) Simulating Genetic Strategies for Increased Yield Potential in Irrigated, Tropical Environments. *Field Crops Research*, **51**, 5-18. https://doi.org/10.1016/S0378-4290(96)01044-1

[39] Aggarwal, P.K., Talukder, K.K. and Mall, R.K. (2000) Potential Yields of the Rice-Wheat System in the Indo-Gangetic Plains in India. Rice-Wheat Consortium Paper Series 10. Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, India and Indian Agricultural Research Institute, New Delhi, 11 p.

[40] Mall, R.K. and Aggarwal, P.K. (2002) Climate Change and Rice Yields in Diverse Agro-Environments in India. I. Evaluation of Impact Assessment Models. *Climate Change*, **52**, 315-330. https://doi.org/10.1023/A:1013702105870

[41] Jones, J.W., Hunt, L.A., Hoogenboom, G., Godwin, D.C., Singh, U., Tsuji, G.Y., Pickering, N.B., Thomton, P.K., Bowen, W.T., Boote, K.J. and Ritchie, J.T. (1994) Crop Models. In: Tsuji, G.Y., Uehera, G. and Balas, S., Eds., *DSSAT Version* 3, Vol. 2, University of Hawaii, Honolulu, 284 p.

[42] Maniruzzaman, M., Biswas, J.C., Hossain, M.B., Haque, M.M., Naher, U.A., Biswas, A., Choudhury, A.K., Akhter, S., Ahmed, F., Rahman, M.M. and Kalra, N. (2017) Evaluating the CERES-Rice Model under Dry Season Irrigated Rice in Bangladesh: Calibration and Validation. *Journal of Agricultural and Crop Research*, **5**, 96-107.

[43] Pathak, H., Ladha, J.K., Aggarwal, P.K., Peng, S., Das, S., Singh, Y., Singh, B., Kamra, S.K., Mishra, B., Sastri, A.P.R.A.S., Aggarwal, H.P., Das, D.K. and Gupta, R.K. (2003) Trends of Climate Potential and On-Farm Yields of Rice and Wheat in the

Indo-Gangetic Plains. *Field Crops Research*, **80**, 223-234.
https://doi.org/10.1016/S0378-4290(02)00194-6

[44] Mohandas, S., Kareem, A.K., Ranganathan, T.B. and Jeyaraman, S. (1995) Rice Production in India under Current and Future Climates. In: Matthews, R.B., Kropff, M.J., Bachelet, D. and van Laar, H.H., Eds., *Modeling the Impact of Climate Change on Rice Production in Asia*, Cab International and International Rice Research Institute, Los Banos, 165-181.

[45] Krishnan, P., Ramakrishnan, B., Raja Reddy, K. and Reddy, V.R. (2011) High Temperature Effects on Rice Growth, Yield, and Grain Quality. In: Sparks, D.L., Ed., *Advances in Agronomy*, Vol. 111, Academic Press, Burlington, 87-206.

[46] Horie, T., Nakagawa, H., Ceneno, H.G.S. and Kropff, M.J. (1995) The Rice Crop Simulation Model SIMRIW and Its Testing. In: Matthews, R.B., Kropff, M.J., Bachelet, D. and van Laar, H.H., Eds., *Modeling the Impact of Climate Change on Rice Production in Asia*, Cab International and International Rice Research Institute, Los Banos, 51-66.

[47] Krishnan, P., Swain, D.K., Bhaskar B.C., Nayak, S.K. and Dash, R.N. (2007) Impact of Elevated CO_2 and Temperature on Rice Yield and Methods of Adaptation as Evaluated by Crop Simulation Studies. *Agriculture*, *Ecosystems and Environment*, **122**, 233-242. https://doi.org/10.1016/j.agee.2007.01.019

[48] BBS (Bangladesh Bureau of Statistics) (2005) Yearbook of Agricultural Statistics of Bangladesh. Government of Bangladesh, Dhaka.

[49] Baker, J.T., Allen, L.H. and Boote, K.J. (1990) Growth and Yield Responses of Rice to Carbon Dioxide Concentration. *The Journal of Agricultural Science*, **115**, 313-320.

[50] Penning de Vries, F.W.T. (1993) Rice Production and Climate Change. In: Penning de Vries, F.W.T., *et al*., Eds., *Systems Approaches for Agricultural Development*, Kluwer Academic Publishers, Dordrecht, 175-189.
https://doi.org/10.1007/978-94-011-2840-7_10

[51] Matthews, R.B., Kropff, M.J. and Bachelet, D. (1995) Introduction. In: Matthews, R.B., Kropff, M.J., Bachelet, D. and van Laar, H.H., Eds., *Modeling the Impact of Climate Change on Rice Production in Asia*, Cab International and International Rice Research Institute, Los Banos, 3-9.

[52] Dias, M.P.N.M., Navaratne, C.M., Weerasinghe, K.D.N. and Hettiarachchi, R.H.A.N. (2016) Application of DSSAT Crop Simulation Model to Identify the Changes of Rice Growth and Yield in Nilwala River Basin for Midcenturies under Changing Climatic Conditions. *Procedia Food Science*, **6**, 159-163.
https://doi.org/10.1016/j.profoo.2016.02.039

[53] Kim, H.Y., Horie, T., Nakagawa, H. and Wada, K. (1996) Effects of Elevated CO_2 Concentration and High Temperature on Growth and Yield of Rice. II. The Effect of Yield and Its Component of Akihikari Rice. *Japanese Journal of Crop Science*, **65**, 644-651. https://doi.org/10.1626/jcs.65.644

[54] Tashiro, T. and Wardlaw, I.F. (1989) A Comparison of the Effect of High Temperature on Grain Development in Wheat and Rice. *Annals of Botany*, **64**, 59-65.
https://doi.org/10.1093/oxfordjournals.aob.a087808

[55] Biswas, J.C., Sarker, U.K. and Sattar, S.A. (2001) Performance of Some BRRI Varieties Planted Year-Round. *Bangladesh Rice Journal*, **10**, 55-59.

[56] Figueiredo, N., Carranca, C., Trindade, H., Pereira, J., Goufo, P., Coutinho, J., Marques, P., Maricato, R. and Varennes, A. (2015) Elevated Carbon Dioxide and Temperature Effects on Rice Yield, Leaf Greenness, and Phenological Stages Dura-

tion. *Paddy and Water Environment*, **13**, 313-324. https://doi.org/10.1007/s10333-014-0447-x

[57] Horie, T., Matsui, T., Nakagawa, H. and Omasa, K. (1996) Effects of Elevated CO_2 and Global Climate Change on Rice Yield in Japan. In: Omasa, K., Kai, K., Taoda, H., Uchijima, Z. and Yoshino, M., Eds., *Climate Change and Plants in East Asia*, Springer, Berlin, 39-56. https://doi.org/10.1007/978-4-431-66899-2_4